Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

A 11.7
F764 copy 3

United States
Department of
Agriculture

Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Paper
INT-290

May 1982

Fuel and Fire Behavior Prediction in Big Sagebrush

James K. Brown

EXTRA COPY

AUTHOR

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph.D. from the University of Michigan in 1968, all in forestry. From 1961 to 1965 he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Mont., where he conducted research on the physical properties, inventory, and prediction of fuels. He currently is leader of a fire effects and use project in Missoula.

RESEARCH SUMMARY

Fuel properties of big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and *Artemisia tridentata* ssp. *vaseyana*) were sampled in Montana and Idaho and used in mathematical modeling of fire behavior. Relationships between height of sagebrush and crown area, bulk density, size distribution of foliage and stemwood, and fraction dead stemwood are shown.

Sagebrush age related poorly to crown area, height, and bulk density. Surface area to volume ratios of foliage averaged 32 cm^{-1}. Predicted rate of spread and fireline intensity are shown for sagebrush ranging in height from 20 to 120 cm and in coverage from 10 to 40 percent. Grass and forbs ranged from 34 to 170 g/m^2. Sagebrush loading ranged from 0.5 to 10 t/ha and bulk density from 3 to 15 kg/m^3. Rate of spread and intensity for a cured phenological condition were two to three times greater than for uncured. The proportion of dead stemwood had little effect on predicted fire behavior. Verification on three prescribed fires showed reasonably good agreement between observed and predicted rates of spread, but poor agreement for flame length and intensity.

CONTENTS

	Page
Introduction	1
Fuel Characterization	1
Fieldwork	1
Fuel Property Relationships	2
Fire Behavior Modeling	4
Fuel Inputs	4
Predicted Fire Behavior	5
Verification	8
Implications and Conclusions	9
Publications Cited	9

United States
Department of
Agriculture

Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Paper
INT-290

May 1982

Fuel and Fire Behavior Prediction in Big Sagebrush

James K. Brown

INTRODUCTION

Modeling rate of spread and fire intensity in sagebrush can aid fire management planning. Mathematical modeling of fire spread and intensity employing Rothermel's model (1972) has been applied successfully using stylized fuel models in the National Fire-Danger Rating System (Deeming and others 1977) and in nomographs (Albini 1976a).

Slash hazard can be appraised from predicted fuel loadings using a program called HAZARD (Puckett and others 1979). Dynamic modeling of fuels and fire behavior over time was demonstrated in chaparral (Rothermel and Philpot 1973) and in palmetto-gallberry fuel complexes where fire behavior depended on age of rough and height of understory (Hough and Albini 1978).

Except for stylized fuel models, applications of fire behavior modeling have involved relatively continuous and uniform fuels such as slash, chaparral, and southern rough. More difficult is modeling of fire spread and intensity in discontinuous and nonuniform fuels such as sagebrush and other xeric site shrub types found particularly in western United States. Inherent in Rothermel's (1972) model is the assumption that fuels are continuous and homogeneous. Properties such as particle size distribution, loading, and bulk density are considered uniform over a rating area. Arid land shrub types violate these assumptions, often to a considerable degree, because shrubs grow in a discontinuous, patchy pattern. Herbaceous fuels between the shrubs are often sparse or absent.

To increase knowledge of fuels and prediction of fire behavior in sagebrush, a study was undertaken to quantify fuel properties and model fire behavior for a variety of sagebrush conditions. This paper reports on this study by describing relationships between fuel properties and height of sagebrush, and by demonstrating how fire modeling might be applied to sagebrush. The fire behavior predictions show to what extent rate of spread and Byram's fireline intensity (Brown and Davis 1973) vary in sagebrush by height, percent cover, foliage moisture, and fraction dead stemwood. Results offer more potential help in planning fire control operations than in planning prescribed fire. However, in both activities, fire behavior predictions from current models might prove useful.

Characterization of fuels is described first, followed by discussion of fire behavior modeling. Metric units are used throughout the paper because much of it deals with plant dimensions which are more appropriately measured and described in the metric system. The American measurement system is used to describe equivalent units for fire modeling values that might be of particular interest to managers.

FUEL CHARACTERIZATION

Fieldwork

Values of fuel properties required to operate Rothermel's (1972) fire spread model can vary substantially from one area to another. They include bulk density of individual plants, loading of live and dead sagebrush by particle size, and particle surface area-to-volume ratios. Loading is weight per unit area. Bulk density is weight of fuel per unit volume of fuel bed and is typically computed as the ratio of loading-to-fuel depth.

Relationships for predicting foliage and stem biomass developed by Harniss and Murray (1976) for mountain big sagebrush (*Artemisia* ssp. *vaseyana*), Rittenhouse and Sneva (1977) for Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*), and Uresk and others (1977) for basin big sagebrush (*A. tridentata* ssp. *tridentata*) appeared adequate to estimate loading for fire modeling. Frandsen[1] went a step further with the biomass data of Uresk and others (1977) and Rittenhouse and Sneva (1977) by developing an analytical method that divided their biomass into size classes and expressed it as loadings dependent upon crown area and height. Information relating plant dimensions to litter loading, bulk density, particle size distribution, and fraction of dead stemwood was limited or absent in the literature. Thus, this study was designed to establish relationships between these fuel properties and height and age of sagebrush.

Individual plants of subspecies *wyomingensis* and *vaseyana* (hereafter referred to as *A. wyomingensis* and *A. vaseyana*) were sampled because these subspecies occupy extensive areas and are known to be flammable. For each subspecies, 10 plants were measured from each of nine stands scattered from southwest Montana to southern Idaho. Heights and ages of sampled plants are shown in table 1.

[1] Frandsen, William H. Modeling big sagebrush as fuel. Manuscript in process. USDA For. Serv., Intermt. For. and Range Exp. Stn., Ogden, Utah

Table 1.—Height and age of sampled sagebrush plants

Height	Number plants		Age	Number plants	
	A. vaseyana	*A. wyomingensis*		*A. vaseyana*	*A. wyomingensis*
cm			*Years*		
0- 20	4	4	0-10	19	24
21- 40	23	25	11-20	31	27
41- 60	25	29	21-30	21	13
61- 80	30	27	31-40	13	12
81-100	8	5	41-50	3	7
			51-60	3	7

For selected plants, the following measurements were taken:

1. Height from the ground to the tallest point on the plant; sporadic or occasional seed stalks were disregarded.
2. Length of long axis of crown in plain view.
3. Length perpendicular to long axis at the widest point.
4. Height from ground to beginning of crown; crown is recognized by the existence of foliage or dense fine dead branchwood that once supported foliage.
5. Crown shape based on integration of plan shape and profile shape (Mawson and others 1976).
6. Diameters measured twice perpendicularly on main stems at ground level or on secondary stems arising within 15 cm of the ground.
7. Fraction of stemwood less than 0.6 cm in diameter that is dead, estimated for each secondary stem.
8. Age of plant by counting growth rings.
9. Percent cover of litter, grass-forbs, and soil occurring beneath the perimeter of each plant; estimated ocularly.
10. Loading of litter, grass, and forbs beneath sagebrush plants.

Material for weighing was collected from 10- by 10-cm and 20- by 20-cm plots placed beneath each plant where litter and herbaceous vegetation appeared average in amount. Dead-to-live ratios were determined for grass and forbs collected in late June after new growth occurred.

Fuel Property Relationships

Loading

Loading was determined from estimates of individual plant biomass divided by estimates of individual plant crown area. Equations were derived by Frandsen[1] using data from Rittenhouse and Sneva (1977) for *A.* [*tridentata*] *wyomingensis*:

$$m = 10^{-2.2522} A^{0.5553} H^{1.1780} \quad (1)$$

$$m = 10^{-3.1639} A^{0.7409} H^{1.7351} \quad (2)$$

where:

m = weight, grams
A = crown area, square centimeters
H = sagebrush height, centimeters.

For the fire behavior modeling exercise, individual plant biomass was estimated from equation (1) for foliage, and equation (2) for woody biomass. Except for these estimates of biomass, all other fuel relationships were determined from the field study described in this paper. To solve equations (1) and (2), crown area was predicted from height. Loading was computed by dividing individual plant weight by crown area.

Crown Area

The Pearson correlation coefficient for crown area related to age was 0.16 for *A. vaseyana* and 0.18 for *A. wyomingensis*. The weak correlations probably resulted from the characteristic of sagebrush to grow rapidly in height and crown area for several years followed by a long period of very slow growth. To model fuels dynamically, a relationship between age of plants and fuel characteristics is desirable. Unfortunately, the relationship between age of sagebrush and crown area was poor. Because crown area is essential to estimating sagebrush loading, dynamic modeling based on age was impractical. The relationship between crown area and height, however, was considerably more precise than between crown area and age (table 2), and was picked for modeling fuel characteristics. Although a test of differences in slope and intercept between *A. wyomingensis* and *A. vaseyana* was highly significant, the equation for combined data was selected because the difference was small.

Bulk Density

Bulk density was computed using weights of foliage plus 0- to 0.6-cm live and dead stemwood, and foliage plus 0- to 2.5-cm live and dead stemwood. The latter was used for fire behavior modeling. Weight of stemwood greater than 2.5 cm was omitted from the calculation of bulk density because this size class is believed to contribute a relatively small amount of heat to the flame front, and it can distort the influence of bulk density on modeled fire behavior. Fuel bed volumes used to compute bulk densities were estimated as the crown volumes of each plant. The volume between the bottom of the crown and the ground, which often was negligible, was excluded from the volume estimate. Crown shapes approximated primarily elliptical ellipsoids and elliptical paraboloids.

Bulk density varied greatly; however, it was significantly related inversely to height (table 2). Differences in regression slopes between the subspecies were significant at the 0.05 level. However, because variation was substantial and the differences between species not large enough to be important in predicting fire behavior, the combined data equation was used in fire modeling. The correlation coefficient between bulk density and age was 0.26 for *A. vaseyana* and nonsignificant -0.02 for *A. wyomingensis*.

Table 2.—Regression equations for sagebrush[1]

Regression equation	Sub-species	Number plants	R^2	Standard error	a	b
ln A = a + b(lnH)	Vas.	89	0.71	0.5732	-10.1554	1.9092
	Wyo.	89	.67	.5712	-10.2374	1.9254
	All	178	.69	.5690	-10.1944	1.9168
ln BD1 = a + b(lnH)	Vas.	89	.22	.5919	-3.0553	.6693
	Wyo.	89	.38	.5949	-1.2526	-1.0930
	All	178	.29	.3629	-2.2274	-.8604
F = a + b(lnH)	Vas.	89	.60	.0191	.3410	-.05007
	Wyo.	89	.50	.0137	.2700	-.03242
	All	178	.55	.0170	.3088	-.04210
P1 = a+b(1/H)	All	178	.48	.0261	.4072	2.2318
P2 = a+b(H)	All	178	.46	—	.9796	-.002454
BD2 = b(BD1)	All	178	.99	.00091	NS	1.8286
lnD = a+bln(age)	Vas.	89	.23	.7148	-2.7913	.5407
	Wyo.	89	.28	.7245	-3.3661	.6166
	All	178	.24	.7380	-3.0742	.5772

[1] A = crown area, square meters;
H = plant height, centimeters;
BD1 = bulk density of foliage and 0- to 0.6-cm stemwood, grams per cubic centimeter;
BD2 = bulk density of foliage plus 0- to 2.5-cm stemwood, grams per cubic centimeter;
F = fraction of foliage;
P1 = fraction of foliage plus 0- to 0.6-cm stemwood;
P2 = fraction of foliage plus 0- to 2.5-cm stemwood; and
D = fraction of 0- to 0.6-cm stemwood that is dead.

Size Proportions

Fractions of foliage and stemwood were determined for each stem using weight and diameter relationships developed by Brown (1976). For plants having more than one stem, the fractions of foliage and stemwood for the entire plant were computed using the sum of all secondary stem weights.

The fraction of plant biomass in foliage had a slight inverse relationship with height (table 2). The difference in regression estimates between subspecies was significant at the 0.01 level, but the differences were very small and unimportant for fire modeling. Cumulative proportions of stemwood were related to height for the combined subspecies (table 2). The fractions of foliage and 0- to 0.6-cm and 0.6- to 2.5-cm stemwood determined by subtracting cumulative proportions remained reasonably constant with change in height (fig. 1). A comparison of the fractions of foliage and stemwood for threetip sagebrush (*A. tripartita*) from Murray[2] and for *A. vaseyana* and *A. wyomingensis* showed rather small differences. *A. tripartita* had a somewhat greater proportion of foliage and 0- to 0.6-cm stemwood.

Fractions Dead

The fraction of dead stemwood varied substantially with height. Attempts at regression analysis including transformations failed to uncover unreasonable fits throughout the range of height. Thus, the data were plotted and visually divided into the four height groups shown in table 3.

Fraction dead correlated more closely with age than with height (table 1). In four stands of *A. tridentata*, Murray (1975) observed dead-to-live ratios ranging from 0.04 at a stand age of 12 years to 0.27 at 45 years. Uresk and others (1977) found that dead stemwood of *A. tridentata* averaged 11 percent of the total plant biomass. Other data[3] for *A. tridentata* showed percent dead of the total plant to range from 43 percent at a height of 20 cm to 54 percent at 100 cm.

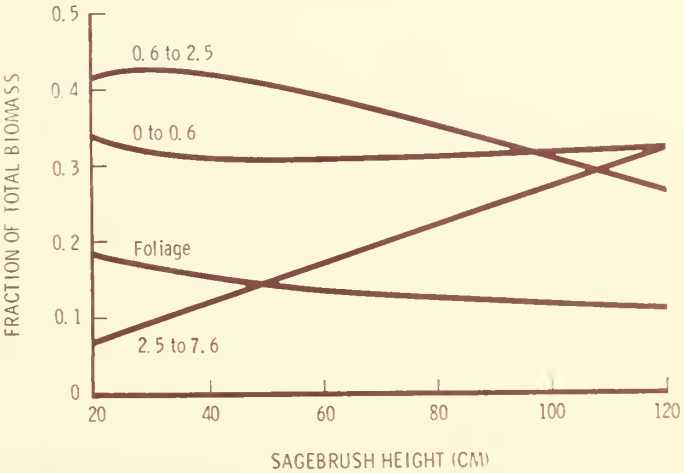

Figure 1.—Fractions of foliage, 0- to 0.6-cm, 0.6- to 2.5-cm, and 2.5- to 7.6-cm stemwood (live and dead together) for *A. vaseyana* and *A. wyomingensis* combined.

[2] Murray, Robert B., and Quin Jacobson. An evaluation of dimension analysis for predicting shrub biomass. Manuscript in process. USDA Serv. Agric. Res., (submitted to J. Range Manage.).

[3] Data from Robert Martin, USDA For. Serv., Pac. Northwest For. and Range Exp. Stn., Bend, Oreg.

Table 3.—Fraction of 0- to 0.6-cm stemwood that is dead by height classes and age

Height interval	Average height	Number observed	Fraction dead	Average age
— — — — — cm — — — — —				Years
10-24	19	17	0.071	9
25-34	30	24	.168	16
35-79	58	125	.349	24
80-104	87	12	.484	36

Ratios of dead-to-live grasses and forbs were plotted over sagebrush age and loading of live grass-forbs. This ordination failed to show any relationship between the dead-to-live ratio and kind of grass (bunchgrass or annual grass), degree of utilization, or live loading. Some ratios were infinitely small and others excessively large; thus, the median ratio rather than the average seemed more appropriate to use in fire modeling. The median dead-to-live ratio was 0.77, which is 43 percent of the total plant weight.

Litter and Grass Beneath Sagebrush

Coverage of litter averaged 52 percent. Loading of litter, including bare patches of soil beneath plants, averaged 78 g/m^2. Grass loadings ranged from 22 to 224 g/m^2 with a median value of 88. Forbs were sparser, having a median loading of 20 g/m^2.

Foliage Surface Area-to-Volume Ratio

Surface area-to-volume ratios describe the amount of surface area surrounding a unit volume of particle and relate to ease of ignition. For sagebrush foliage, they were determined by measuring thickness on a sample of leaves and computing as:

$$\sigma = 2/t \quad \text{(Brown 1970)} \qquad (3)$$

where:

σ = surface area-to-volume ratio, cm^{-1}
t = leaf thickness, cm.

Ten leaves from a mixture of the subspecies *A. wyomingensis* and *A. vaseyana* were chosen at random from each of three sites in Montana and Idaho. For the three sites, σ averaged 32 cm^{-1};

	Location		
	Dillon	Mackay	Challis
Average thickness, mm	0.716	0.677	0.553
Average σ, cm^{-1}	28.2	30.0	36.7
Stand. dev. σ, cm^{-1}	2.5	3.9	4.5

For stemwood, σ was determined using average diameters of the 0- to 0.6-cm and 0.6- to 2.5-cm size classes (Brown 1976) to solve the surface area-to-volume formula for cylinders:

$$\sigma = 4/d \qquad (4)$$

where:

d = stem diameter, cm.

Height Estimation

Since loading and size proportions related reasonably well to height, height was used as the primary independent variable for modeling fuels. Height and age, however, were poorly correlated (r = 0.24, *A. vaseyana* and r = 0.27, *A. wyomingensis*). Thus, use of age for dynamic modeling of sagebrush fuel and fire behavior over time would yield inconclusive information.

An important practical question is: How should managers estimate height to properly determine loading? This was investigated by first solving equation (2) for height given an average loading for each stand. Next, the average stand height from solution of the loading equation was compared to an average maximum height of each stand obtained by averaging the two largest heights per stand. The ratio of average height-to-average maximum height was 0.802. In defining the top of a stand of sagebrush by scanning, a person tends to view the tops of the highest plants. Thus, a rule for determining proper height is to take 0.8 of the average large plant height or essentially 0.8 of an eyeball scan of the sagebrush.

FIRE BEHAVIOR MODELING

Fuel Inputs

Fire behavior was modeled for two phenological situations that reflect relatively lush vegetation of early summer and cured vegetation of fall:

Case A: All sagebrush foliage alive; 57 percent of grasses and forbs alive.

Case B: One-third of sagebrush foliage (the ephemeral leaves) considered dead; all grasses and forbs cured or dead.

For each phenological situation fuel loadings were varied to correspond with sagebrush ranging from 20 to 120 cm in height and 10 to 40 percent in cover. Loadings of grasses and forbs ranged from 34 to 168 g/m^2 (300 to 1,500 lb/acre). These conditions were chosen in order to show the extent to which rate of spread and fireline intensity vary in the sagebrush type.

Rate of spread and fireline intensity were predicted using the computer program FIREMOD (Albini 1976b). Preliminary modeling of fire behavior was undertaken to determine the importance of litter and herbaceous vegetation beneath sagebrush plants. Litter, grasses, and forbs existing within the crown circumference of sagebrush were considered part of the sagebrush for fire behavior modeling. Herbaceous vegetation existing among sagebrush plants was handled separately from sagebrush itself for predicting fire behavior.

Preliminary modeling showed that for large sagebrush plants, litter had little influence on rate of spread and fireline intensity. For small plants, however, presence of litter significantly influenced fire behavior. Because litter was an important fuel in small sagebrush, an average litter loading of 77.3 g/m^2 (690 lb/acre) was used as an input to all sagebrush modeling. Litter loading appeared unrelated to characteristics of sagebrush, thus it could not be predicted as a function of the sagebrush.

To evaluate the importance of modeling grass beneath sagebrush of varying heights, fire behavior was predicted at two diverse grass loadings distributed in three ways: (a) equally within and between sagebrush, (b) twice as much beneath as between sagebrush, and (c) three times as much beneath as between sagebrush. Results showed

that, for given grass loadings, varying the ratio of grass beneath and between sagebrush had little influence on predicted fire behavior. Thus, for further modeling of fire behavior, herbaceous vegetation was assumed to be evenly distributed beneath and between sagebrush.

Fire behavior predictions were based on sagebrush fuel loadings and bulk densities shown in tables 4 and 5. The loadings in table 5 can be expanded to include stemwood greater than 2.5 cm by multiplying them times the expansion factor. The following percent fuel moisture contents were assumed:

	Dead	Alive
Shrub foliage	5	65
Shrub stems	7	65
Herbaceous vegetation	5	80
Litter	5	—

The moisture content for living herbaceous vegetation was derived from air-dry moisture contents of wheatgrass (*Agropyron* sp.) and fescue (*Festuca* sp.) at the time of seed ripening (USDA Forest Service Region 4 range manual). The living sagebrush moisture content represents moisture levels from August into autumn according to Britton[4] and Olson (1978).

Table 4.—Fuel loading and bulk density of individual sagebrush plants used in fire behavior modeling

Sagebrush height	Foliage loading	Stemwood loading		Bulk density
		0 to 0.6 cm	0.6 to 2.5 cm	
cm	— — — — — g/m^2 — — — — — —			kg/m^3
20	108	199	244	15.0
40	175	353	478	9.25
60	237	535	675	5.82
80	295	737	827	4.54
100	350	956	928	3.75
120	401	1190	970	3.20

The fraction of dead stemwood in sagebrush was:

Sagebrush height	Diameter class	
	0 to 0.6 cm	0.6 to 2.5 cm
cm		
< 25	0.07	0.11
25-34	.17	.11
35-79	.35	.11
80 +	.48	.11

[4] Data from Carlton Britton, Texas Tech University.

Fuel particle surface area-to-volume ratios (cm^2/cm^3) were:

Sagebrush foliage	32.8
0- to 0.6-cm stemwood	22.2
0.6- to 2.5-cm stemwood	4.76
Litter	49.2
Herbaceous vegetation	98.4

Other fuel variables required for fire behavior modeling, such as heat content, particle density, and mineral contents, were handled as constants and reside in the FIREMOD program.

Predicted Fire Behavior

Rate of Spread

Rate of spread was computed as an average of spread rates for grass and sagebrush, each weighted by their respective percent cover. The approach of weighting spread rates by percent cover of component fuel types appears to furnish more realistic predictions than does the alternative of averaging fuels before predicting spread rates. This is especially true when distinctly different kinds of fuel exist within a single vegetative type (Brown 1981).

Rates of spread at 13 km/h (8 mi/h) midflame height windspeed are shown in figure 2 for case A and figure 3 for case B. Rate of spread varies considerably because of changes in grass loading rather than sagebrush loading. Rate of spread is very sensitive to the amount of finely divided dead fuel. To illustrate, in case B, where all grass and one-third of the sagebrush foliage is assumed dead. rates of spread are approximately two to three times higher than in case A. Caution is advised in interpreting figures 2 and 3 because some combinations of grass loading and sagebrush cover may be unrealistic. For example, a vegetative community composed of 40-percent sagebrush cover and 170 g/m^2 (1,500 lb/acre) of grass probably does not exist.

For the low coverage of sagebrush, rate of spread is almost totally dependent on the rate of spread of grass. Even large sagebrush plants contribute little to rate of spread because 80 to 90 percent of the spread rate is determined by grass. However, as coverage of sagebrush increases to 30 or 40 percent, rate of spread is noticeably increased, especially for the taller plants. The effect of an increased sagebrush coverage on rate of spread is illustrated in figures 2 and 3 by the crossover of curves for 10 and 40 percent cover. Rates of spread for grass and sagebrush are equal at the crossover point.

Table 5.—Fuel loading of sagebrush foliage and 0- to 2.5-cm diameter stemwood at varying heights and percent covers

Sagebrush height	Percent cover								Expansion factor
	10		20		30		40		
cm	— — — — — — — — — — *t/ha (tons/acre)* — — — — — — — — — —								
20	0.55	(0.26)	1.1	(0.49)	1.7	(0.74)	2.2	(0.98)	1.07
40	1.0	(.45)	2.0	(.90)	3.0	(1.3)	4.0	(1.8)	1.10
60	1.4	(.64)	2.9	(1.3)	4.3	(1.9)	5.8	(2.6)	1.20
80	1.9	(.83)	3.7	(1.7)	5.6	(2.5)	7.4	:3.3)	1.28
100	2.2	(1.0)	4.5	(2.0)	6.7	(3.0)	8.9	(4.0)	1.36
120	2.6	(1.1)	5.1	(2.3)	7.7	(3.4)	10.2	(4.6)	1.46

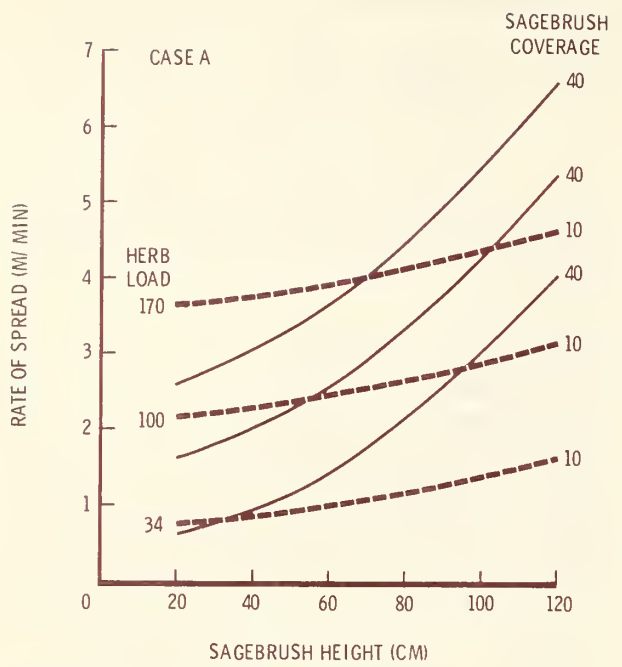

Figure 2.—Rate of spread at 13-km/h (8-mi/h) midflame-height windspeed and grass and forb loadings of 170 g/m^2 (1,500 lb/acre), 100 g/m^2 (900 lb/acre), and 34 g/m^2 (300 lb/acre). Grass and forbs are 57 percent alive and sagebrush foliage entirely alive.

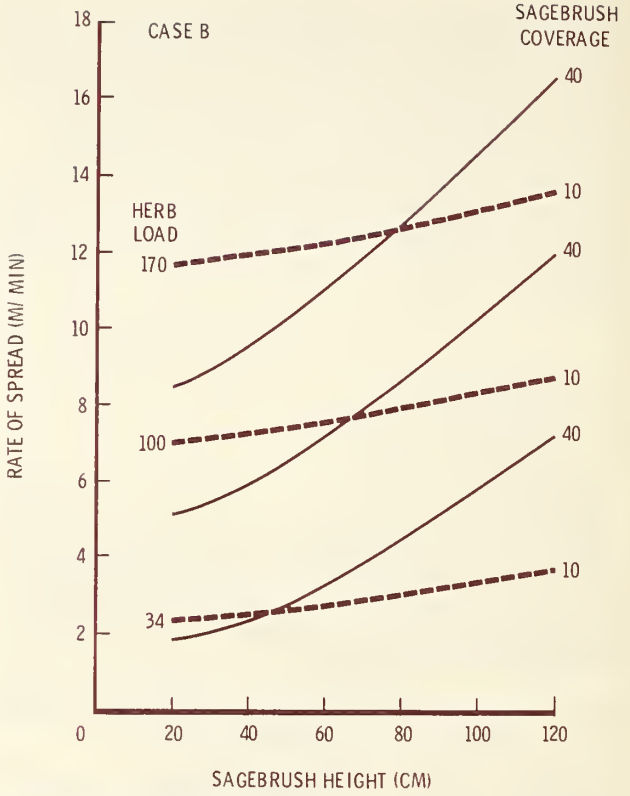

Figure 3.—Rate of spread at 13-km/h (8-mi/h) midflame-height windspeed and grass and forb loadings of 170 g/m^2 (1,500 lb/acre), 100 g/m^2 (900 lb/acre), and 34 g/m^2 (300 lb/acre). Grass and forbs are entirely dead and sagebrush foliage is one-third dead.

The sagebrush community is typically discontinuous patches of grass, shrubs, and bare soil. Because current fire modeling cannot deal adequately with discontinuities, predicted fire behavior at low fuel loadings and windspeeds can be misleading. Although fire will not spread at sparse loadings and low windspeeds, mathematical predictions based on the uniform fuel assumption show that fires do spread. Thus, the validity of predicted fire behavior must be evaluated using other knowledge about conditions that limit fire spread.

Reports on prescribed burning in sagebrush (Britton and Ralphs 1979) and pinyon-juniper (Klebenow and Bruner 1976), and discussion with several people who have burned sagebrush, suggest some minimum conditions required for fire to spread:

1. For grass at 35 to 60 g/m^2 (300 to 500 lb/acre), at least 6 to 8 km/h (4 to 5 mi/h) of wind is needed to spread fire, depending on fuel distribution. Bunchgrasses will require more windspeed or loading than other grasses to satisfy minimal conditions for spread of fire.
2. For grass at 35 g/m^2 (300 lb/acre) and less, and sagebrush at less than 20 percent coverage, a wind of 16 km/h (10 mi/h) or more may be required to spread fire.

Fireline Intensity

Fireline intensities for case A are shown in figure 4 and for case B in figure 5. Average intensities determined from intensities of sagebrush and grass weighted by their respective coverage are presented for 10 and 40 percent cover of sagebrush. Intensity is also graphed for sagebrush alone, or in other words, for 100 percent sagebrush. The weighted average intensities are probably of little practical value because they fail to reflect either the intensity of grass alone or of sagebrush. Intensity of sagebrush alone should provide a more realistic and useful estimate of fireline intensity, particularly for fires where the time between ignition of adjacent sagebrush plants is less than the burnout time of individual plants. Predicted fireline intensities of grass are also of less importance because they range from 10 to 100 times less than for sagebrush alone (fig. 6).

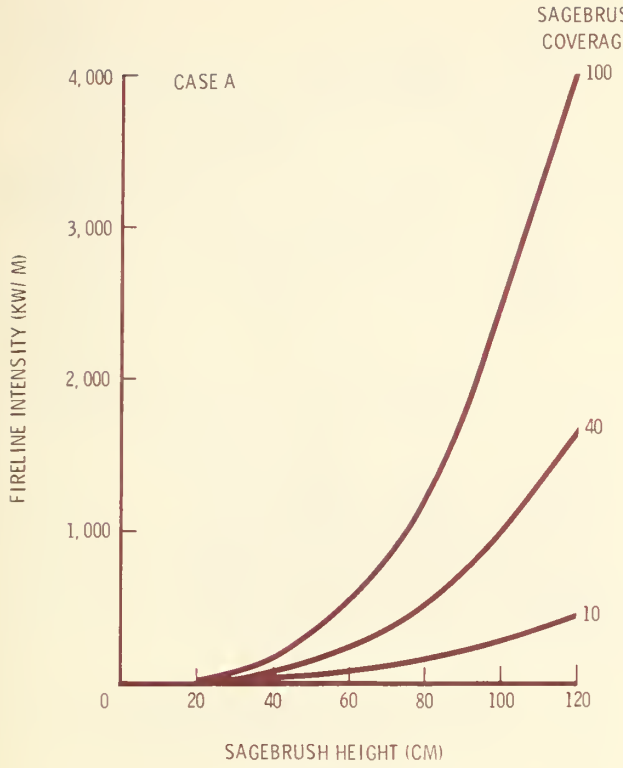

Figure 4.—Fireline intensity at 13-km/h (8-mi/h) midflame-height windspeed and 100 g/m^2 (900 lb/acre) of grass and forbs. Grass and forbs are 57 percent alive and sagebrush entirely alive.

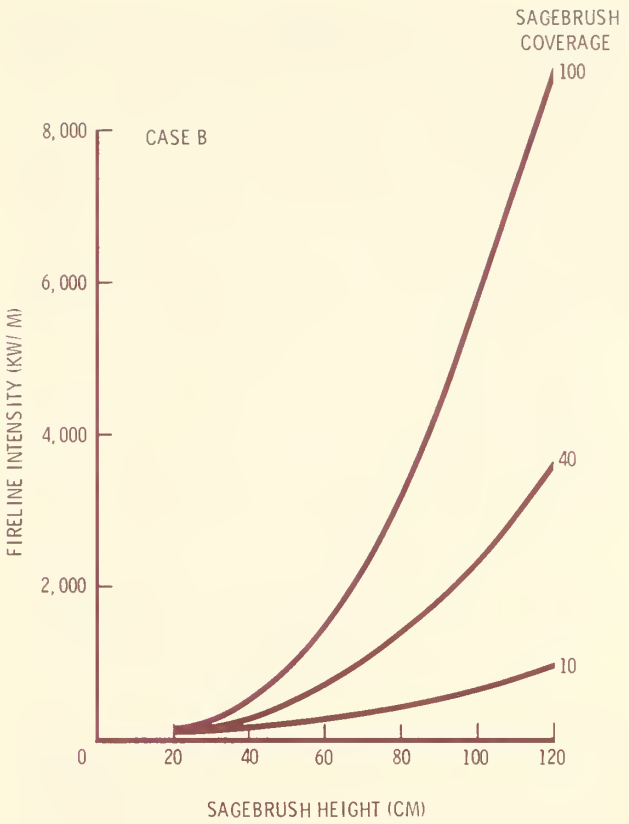

Figure 5.—Fireline intensity at 13-km/h (8-mi/h) midflame-height windspeed and 100 g/m^2 (900 lbs/acre) of grass and forbs. Grass and forbs are entirely dead and sagebrush foliage is one-third dead.

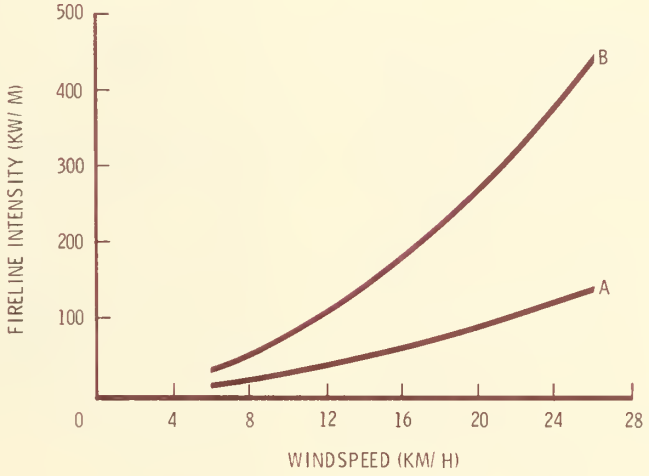

Figure 6.—Fireline intensity of grass and forbs for cases A and B at 100 g/m^2 (900 lb/acre) and varying midflame-height windspeeds.

Fuel moisture content greatly influences fireline intensity, as is shown in comparing cases A and B (figs. 4 and 5). Intensities for the completely cured condition average about 2.5 times greater than for the higher fuel moisture condition of early summer.

Conceptually, fireline intensity is the amount of energy released from a cross section of unit width through the propagating portion of a fire front over a specified unit of time. To help interpret Byram's fireline intensities in terms of working near fire and controlling it, the following tabulation taken from Puckett and others (1979) is presented:

Intensity	Flame length	Fire situation
kW/m (Btu/ft/s)	*m (ft)*	
70 to 170 (20 to 50)	0.6 to 0.9 (2 to 3)	Easily attacked and controlled. People can work right up to the edge of the fire without extra protection.
345 (100)	1.2 (4)	This is about the limit beyond which people are unable to work at the fire edge. Direct attack with hand crews may be difficult.
1 700 to 2 400 (500 to 700)	2.4 to 2.7 (8 to 9)	Spotting begins to be a problem, and the limit of direct attack is probably reached in this range of intensities.

As an example in using this information with figures 4 and 5, excessive fireline intensities taken as 2 000 kW/m exist for sagebrush greater than about 60 cm for case B and 90 cm for case A. Different windspeeds will alter fireline intensities and, of course, fire management implications.

Effects of Wind and Slope

Estimates of fire behavior in figures 2 through 5 can be adjusted for certain windspeeds using figure 7. The adjustment factors are ratios of rates of spread at 26- to 13-km/h (16- to 8-mi/h) windspeed and at 13- to 6-km/h (8- to 4-mi/h) windspeed. The adjustment factors for intensity were determined similarly. Figure 7 was developed for case A. For case B, add 0.1 to the case A adjustment factor for intensity and 0.3 for rate of spread. The wind adjustment factors vary with sagebrush height and other variables. However, the adjustment factors are approximately 3 for rate of spread and 2.5 for intensity. Doubling windspeed from 13 to 26 km/h (8 to 16 mi/h) increases rate of spread approximately 3 times and intensity 2.5 times. Cutting windspeed in half from 13 to 6 km/h (8 to 4 mi/h) reduces rate of spread by a factor of 3 and intensity by a factor of 2.5. Fire behavior could be interpolated between 6 and 26 km/h (4 and 16 mi/h); however, predictions below 6 km/h (4 mi/h) are not recommended because of inadequacies in the modeling.

Figures 2 through 5 are based on horizontal terrain. For a 30 percent slope, rate of spread and intensity can be expected to increase 2 to 3 times over the zero slope estimates, and 4 to 7 times for a 50 percent slope. The effects of wind and slope on rate of spread and intensity are analytically complex. Graphical determination of rate of spread and intensity as functions of fuel moisture content, windspeed, and slope require use of nomographs such as presented by Albini (1976a).

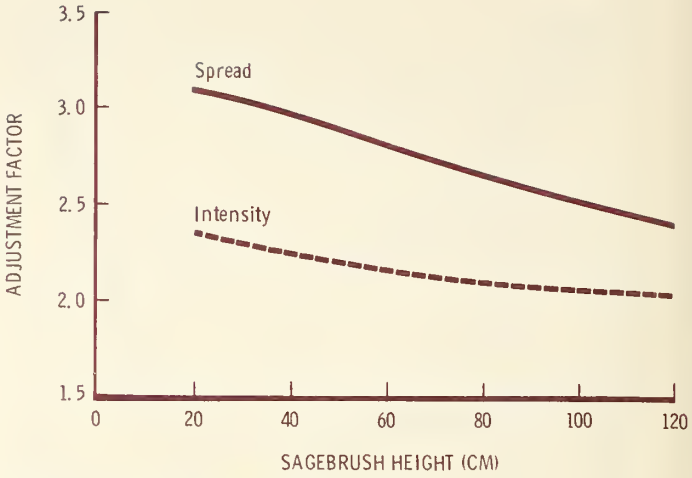

Figure 7.—Adjustment factors for estimating rate of spread and fireline intensity from a windspeed of 13 to 6 km/h (8 to 4 mi/h) and 13 to 26 km/h (8 to 16 mi/h) for case A. For case B, add 0.3 to the adjustment factor for rate of spread and add 0.1 for intensity.

Effects of Dead Stemwood

The proportion of dead stemwood in sagebrush was increased to evaluate the relative influence of shrub decadence. The fractions of dead stemwood used in modeling decadent conditions were:

Sagebrush height, cm	Fractions of stemwood considered dead	
	0 to 0.6 cm	0.6 to 2.5 cm
< 25	0.07	0.45
25 to 34	.35	.45
35 to 79	.45	.45
80 +	.55	.45

The change in fire behavior from original to decadent conditions was an increase of approximately 5 percent for rate of spread and 10 percent for intensity. The small increase in predicted fire behavior due to decadence is probably because most of the stemwood is represented by fairly small surface area-to-volume ratios. The original conditions are averages from data gathered during summer 1978. The decadent conditions are hypothetical. The fractions of dead could be higher; although if they were higher, predicted fire behavior probably would not increase greatly.

Verification

To test the accuracy of predicted fire behavior in the sagebrush vegetation type, appropriate data were located for prescribed burns in three different areas:

1. Oregon—In two experimental burns, reported by Britton and others (1977), rate of spread and flame length were measured and fireline intensity estimated.

2. Montana—A single prescribed burn with several observation periods was conducted near Dillon. Flame length was estimated and data supplied by Ed Mathews,

Montana Department of Natural Resources, Division of Forestry.

3. Idaho—On a prescribed fire near Challis, rate of spread and flame length were measured and data supplied by Steve Bunting, University of Idaho.

Estimates of windspeed, slope, fine fuel moisture, grass and forb loading, and height and coverage of sagebrush were obtained for the burns and used in FIREMOD to predict rate of spread, flame length, and fireline intensity. However, because data were not collected to test the fire models specifically, single observed and predicted values were not determined. Rather, a range of predicted and observed values were compared.

Agreement between observed and predicted rates of spread was considered good. At the worst, one burning period was underpredicted by about 50 percent. Agreement between observed and predicted flame lengths, however, was poor. Flame lengths were consistently predicted at about one-half of the observed values. Fireline intensity was estimated from fuel consumption on the Oregon fires; for the other sites it was estimated using flame lengths in Byram's equation and solving for intensity:

$$L = 0.45\, I^{0.46} \quad (5)$$

where:

L = flame length, feet

I = fireline intensity, Btu/ft/s.

Predicted fireline intensities were 3 to 6 times less than the observed values. Predicted flame lengths and fireline intensities were computed using fuel characteristics of sagebrush alone. The poor agreement between observed and predicted intensity values demonstrates the need to interpret figures 3 and 4 with caution. The limited verification reported here indicates that the figures show intensities that are low by at least a factor of 2.

There may be two reasons for the poor verification of flame lengths and intensities. First, the field observations of flame length may not agree well with the definition of flame length embodied in the mathematical predictions. Second, the combustion of sagebrush in the flame front may proceed at a greater rate than predicted. The reasons for this are speculative. One possibility is that the fractional weight loss of different sized fuel particles is greater than predicted by Rothermel's (1972) spread model. Albini[5] derived an alternative formula for fireline intensity based on fractional weight loss data in slash fuels that is currently used to evaluate slash hazard (Puckett and others 1979). This approach may improve accuracy of predicting fireline intensity in sagebrush as well.

IMPLICATIONS AND CONCLUSIONS

This study demonstrates the current state of knowledge in modeling fuels and fire behavior in sagebrush communities. The most appropriate application is probably in identifying control difficulties and situations leading to erratic and dangerous fire behavior. The fire behavior predictions are particularly useful for illustrating the relative differences in fire behavior between various fuel and weather conditions, such as between cured and uncured vegetation, varying heights and coverages of sagebrush, differing quantities of grasses and forbs, and varying windspeeds and slopes.

Perhaps the weakest aspect of current fire behavior modeling is the inability to predict minimum fuel, weather, and topographic conditions required for fire to spread in a sustained manner. Particularly needed for planning prescribed fire is information on combinations of fuel loading, fuel moisture content, and windspeed that permit fire to spread. Properly designed field experiments to verify mathematical models of rate of spread and intensity in sagebrush are also needed to assure reliable information for a variety of other fire management applications.

[5] Albini, Frank A. 1976. Assessment of fire hazard created by tree-cutting activities. Unpubl. rep. on file at the Intermt. For. and Range Exp. Stn., Northern Forest Fire Laboratory, Missoula, Mont. 59806.

PUBLICATIONS CITED

Albini, Frank A.
1976 a. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30, 92 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Albini, Frank A.
1976b. Computer-based models of wildland fire behavior: a user's manual. USDA For. Serv., Intermt. For. and Range Exp. Stn., Misc. Publ., 68 p. Ogden, Utah.

Britton, Carlton M., B. L. Karr, and F. A. Sneva.
1977. A technique for measuring rate of fire spread. J. Range Manage. 30(5):395-397.

Britton, Carlton M., and Michael H. Ralphs.
1979. Use of fire as a management tool in sagebrush ecosystems. *In* The Sagebrush Ecosystem: Symp. Proc. [Logan, Utah, 1978]. p. 101-109. Utah State Univ., Logan.

Brown, Arthur A., and Kenneth P. Davis.
1973. Forest fire control and use. 2d ed. 686 p. McGraw-Hill, New York.

Brown, James K.
1970. Ratios of surface area to volume for common fine fuels. For. Sci. 16:101-105.

Brown, James K.
1976. Estimating shrub biomass from basal stem diameters. Can J. For. Res. 6:153-158.

Brown, James K.
1981. Bulk densities of nonuniform surface fuels and their application to fire modeling. For. Sci. 27(4): 667-683.

Deeming, John E., Robert E. Burgan, and Jack D. Cohen.
1977. The National Fire-Danger Rating System—1978. USDA For. Serv. Gen. Tech. Rep. INT-39, 63 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Harniss, Roy O., and Robert B. Murray.
1976. Reducing bias in dry leaf weight estimates of big sagebrush. J. Range Manage. 29:430-432.

Hough, W. A., and F. A. Albini.
1978. Predicting fire behavior in palmetto-gallberry fuel complexes. USDA For. Serv. Res. Pap. SE-174, 44 p. Southeast. For. Exp. Stn., Asheville, N.C.

Klebenow, Donald A., and Allen D. Bruner.
1976. Determining factors necessary for prescribed burning. *In* Use of Prescribed Burning in Western Woodland and Range Ecosystems: Symp. Proc. [Logan, Utah, 1976]. p. 69-77. Utah State Univ., Logan.

Mawson, Joseph C., Jack Ward Thomas, and Richard M. DeGraaf.
1976. PROGRAM HTVOL - The determination of tree crown volume by layers. USDA For. Serv. Res. Pap. NE-354, 9 p. Northeast. For. Exp. Stn., Broomall, Pa.

Murray, Robert B.
1975. Effect of *Artemisia tridentata* removal on mineral cycling. Ph.D. diss. Wash. State Univ., Pullman. 190 p.

Olson, Craig Mackay.
1978. Foliar moisture content and prescribed burning in Lava Beds National Monument, Calif. M.S. thesis. Univ. Wash., Seattle.

Puckett, John V., Cameron M. Johnston, Frank A. Albini, and others.
1979. User's guide to debris prediction and hazard appraisal. 37 p. USDA For. Serv., North. Reg., Missoula, Mont.

Rittenhouse, L. R., and F. A. Sneva.
1977. A technique for estimating big sagebrush production. J. Range Manage. 30:68-70.

Rothermel, Richard C.
1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, 40 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Rothermel, Richard C., and Charles W. Philpot.
1973. Predicting changes in chaparral flammability. J. For. 71:640-643.

Uresk, D. W., R. O. Gilbert, and W. H. Rickard.
1977. Sampling big sagebrush for phytomass. J. Range Manage. 30:311-314.

Brown, James K.
1982. Fuel and fire behavior prediction in big sagebrush.
USDA For. Serv. Res. Pap. INT-290, 10 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Relationships between height of big sagebrush and crown area, fuel loading, bulk density, size distribution of foliage and stemwood, and fraction dead stemwood are presented. Based upon these relationships, modeled rate-of-fire spread and fireline intensity are shown for sagebrush ranging in height from 20 to 120 cm and in coverage from 10 to 40 percent. Verification of predicted fire behavior and applications are discussed.

KEYWORDS: sagebrush, fire behavior modeling, fuel modeling, range fuels

☆ U.S. GOVERNMENT PRINTING OFFICE: 1982—576-026/147 REGION No. 8

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

Field programs and research work units of the Station are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)